Journal of Arid Environments 166 (2019) 91–107

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

GIS-based hydrological modelling to assess runoff yields in ancient-agricultural terraced wadi fields (central Negev desert)

Hendrik J. Bruins[a,*], Hodaya Bithan-Guedj[b,1], Tal Svoray[b,c]

[a] Jacob Blaustein Institutes for Desert Research, Ben Gurion University of the Negev, Sede Boker Campus, 8499000, Israel
[b] Department of Geography and Environmental Development, Ben Gurion University of the Negev, Beer-Sheva, 8410501, Israel
[c] Department of Psychology, Ben Gurion University of the Negev, Beer-Sheva, 8410501, Israel

ARTICLE INFO

Keywords:
Ancient agriculture
Runoff water harvesting
GIS
Spatially explicit hydrological model
D Infinity algorithm
Runoff coefficient

ABSTRACT

Thousands of ancient agricultural terraced fields exist in ephemeral stream valleys in the central Negev desert. Their stone terrace walls captured runoff water, flowing from the surrounding hillslope catchments, to increase moisture in the loess soils of the terraced fields. Geoarchaeological research at the site of Horvat Haluqim discovered evidence for ancient farming and soil manuring in this arid desert region during various archaeological periods. Geographic Information Systems (GIS) and Digital Elevation Models (DEM) enable the development of hydrological models to investigate every ancient terraced field in a non-invasive manner, without disturbing the archaeological remains. We developed a GIS-based hydrological model, coupled with the D-Infinity (Tau DEM) algorithm, to evaluate annual runoff yields in 13 ancient terraced fields at the rural archaeological site of Horvat Haluqim. Our model precisely determined the runoff catchment area, ranging between 0.10 ha and 0.36 ha, of each individual terraced field. Supervised land cover classification, using Erdas Imagine, showed the surface percentages of crusted loess soil and exposed bedrock. Following an evaluation of runoff coefficients established by conventional hydrological studies in the region, we present results of model-calculated runoff overland flow yields. We modelled runoff amounts for each of the agricultural fields during an average year (1989–90) with 88 mm precipitation, a very wet year (1991–92) with 188 mm, and a severe drought year (1999–2000) with only 34 mm rainfall. Our initial results, based on an approximated average annual runoff coefficient of 10%, indicate that runoff water amounts during an average and wet rainfall year appear sufficient to grow agricultural crops in these ancient fields. However, drought years are of course more problematic. The modelling results are supported by the successful growth of trees in similar terraced wadi fields next to Horvat Haluqim, established by the Jewish National Fund. Given the inherent uncertainties involved in modelling, it is encouraging to note that the trees did survive also drought years. Our model may be applied to evaluate the effect of climatic changes on runoff water harvesting systems, looking back into the past and also to assess possible impact of future climate change scenarios in modern water harvesting projects.

1. Introduction

The average annual precipitation in the Negev Highlands at present is approximately 100 mm and the average annual evaporation from a class A pan is about 2600 mm (Goldreich, 2003). Therefore, rainfall amounts are obviously insufficient for dry farming, whether for the production of seasonal food grains (barley, wheat), or perennial trees. Nevertheless, thousands of stone terrace walls exist in ephemeral dry stream valleys (wadi in Arabic, nahal in Hebrew) of the central Negev Highlands (Fig. 1). These terrace walls were built in ancient times to capture runoff rainwater, so that soil moisture is increased considerably in the terraced agricultural fields. Widespread crusted loess soils enabled agriculture in this arid desert region, both in the generation of runoff on the slopes and also in the preservation of captured runoff water in the loess soils of the terraced agricultural fields (Evenari et al., 1982; Shanan and Schick, 1980; Bruins, 1986, 1990; 2012; Ore and Bruins, 2012).

The excavations of ancient terraced fields at the rural archaeological site of Horvat Haluqim (Bruins et al., 1986; 2012; Bruins and Van der Plicht, 2017a, 2017b) (Fig. 1) show that stone terrace walls were built in stream channels, which already contained alluvial loess soils. These soils have a silt-loam texture with an excellent water-holding capacity,

* Corresponding author.
E-mail addresses: hjbruins@bgu.ac.il (H.J. Bruins), hodayagu1@gmail.com (H. Bithan-Guedj), tsvoray@bgu.ac.il (T. Svoray).
[1] Present Affiliation: Israel Antiquities Authority, Jerusalem, Israel.

https://doi.org/10.1016/j.jaridenv.2019.02.010
Received 20 December 2017; Received in revised form 14 February 2019; Accepted 18 February 2019
Available online 14 March 2019
0140-1963/ © 2019 Elsevier Ltd. All rights reserved.

Fig. 1. Map of the Negev showing areas with ancient agricultural wadi terraces, used for farming based on the capture of runoff/floodwater. The locations of meteorological stations, archaeological sites and geographic features mentioned in the text are indicated (adapted from Bruins, 2012).

which is essential to store the captured runoff water for crop growth. The stone terrace walls were first and foremost built to harvest runoff water, but the effect of water capture and the slowing down of the flow of water also induced aggradation of fine loessial sediment transported by the runoff from the hillslope catchments during rainfall events. The gradual soil aggradation on the terraced fields was a distinct additional benefit of runoff water harvesting, leading also to soil harvesting, resulting in increasing soil depth. Shanan (2000) measured the amount of sediment transported from the hillslopes by runoff flows at the reconstructed ancient Avdat Farm (Fig. 1), dated to the Byzantine period (324–640 CE). The pre-farming environment with regard to sediments and soil depth in ephemeral stream channels in the Negev Highlands

was investigated by Avni et al. (2012), using OSL dating.

The areal extent of ancient terraced fields in the region was first surveyed by Kedar (1967), using aerial photographs. The most recent update and evaluation of the spatial distribution of ancient terrace walls in the Negev (Fig. 1) was carried out by Bruins (2012) in relation to a new climatic classification of southern Israel, based on the P/PET index (P = annual precipitation, PET = potential annual evapotranspiration). Most ancient agricultural terrace walls are situated in the Arid Zone, in between the P/PET range of 0.05 and 0.10. Dry farming, based on direct rainfall, is only viable, according to UNEP (1997), in the Semi-Arid Zone and wetter regions, having a P/PET index above 0.20. Therefore, additional water is/was clearly necessary to facilitate agriculture in the central Negev Highlands.

A simple classification system, based on farm design in terms of runoff/floodwater supply was described by Bruins et al. (1986), in which three ancient systems are defined: (1) Terraced Wadi System; (2) Hillside Conduit System; and (3) Diversion System. The latter has the most extensive landscape coverage, involving large wadis from which floodwater is captured by diversion channels. The diverted floodwater is subsequently conducted to terraced fields, situated in the adjacent alluvial valley.

The Terraced Wadi System is probably the oldest and most common in the Negev Highlands (Bruins, 2012), characterised by a series of stone terrace walls in the wadi bed (Ore and Bruins, 2012), without any conduit or diversion channels. Each terraced field in this system, particularly in wadis of low stream order, receives runoff overland flow mainly from the adjacent hillslopes. Our paper is focussed on this system, as presented here in relation to the rural archaeological site of Horvat Haluqim, characterised by terraced wadis of the 1st stream order.

Concerning the chronological span of ancient runoff-capturing terraced fields, the oldest stone wall barrage systems (i.e. terraced wadi), dated to the 7th millennium BCE (Pre-Pottery Neolithic B), is situated in the desert of south-east Jordan (Fuji, 2007; Bruins, 2012). The oldest evidence in the central Negev Highlands for terraced wadi fields has been found by Bruins (2012) at Horvat Haluqim, dated by radiocarbon to about 5000–4700 cal BCE. Other periods found at Horvat Haluqim in relation to terraced wadi fields, dated by radiocarbon (Bruins, 2012; Bruins et al., 2012, 2018; Bruins and Van der Plicht, 2017a, 2017b), are the Late Bronze Age (ca 1550–1200 BCE), Iron Age I (ca 1200–980 BCE), Iron Age II (ca 980–586 BCE), Persian period (539–332 BCE), Roman period (37 BCE–324 CE), and Early Islamic period (640–1099 BCE). Various soil layers in the terraced wadi fields at Horvat Haluqim show unmistakable evidence of manuring by ash from kitchen fires (also containing pieces of animal bones and broken pottery) and from animal dung (Bruins, 2012; Bruins and Jongmans, 2012; Bruins and Van der Plicht, 2017a, 2017b). Agricultural development in other terraced wadi fields in the Negev during the Byzantine and Early Islamic periods has been studied by Avni et al. (2013), using OSL dating.

The Hillside Conduit System, probably developed during the Byzantine period, is characterised by terraced wadi fields that receive runoff mainly as channel flow through conduits built on the adjacent hillslopes, which capture the runoff overland flow and convert it to channel flow. The latter type of flow is much faster than overland flow. Thus significantly more runoff water can be harvested from the adjacent hillslopes and conducted unto the agricultural terraced fields in the valley (Shanan and Schick, 1980; Evenari et al., 1982; Bruins et al., 1986).

There are hundreds of ancient farming units with numerous stone terrace walls in the Negev Highlands (Evenari et al., 1958; Kedar, 1967; Ashkenazi et al., 2012). So far only two ancient farming units, near Shivta and near Avdat (Fig. 1), were reconstructed and investigated in a detailed manner in terms of hydrology and agronomy, using rain gauges and hydrographs to measure the amount of rainfall and resulting runoff flowing unto the terraced fields (Evenari et al., 1982; Shanan and Schick, 1980; Shanan, 2000). Both investigated farming units belong to the Hillside Conduit System.

It is clearly impossible, besides being very costly and labour-intensive, to investigate each and every ancient agricultural field with hydrographs, conventional hydrological fieldwork and agricultural field trials. Moreover, such invasive research is bound to eradicate and alter the original archaeological soil record and related building remains.

As an alternative, Geographic Information Systems (GIS) and Digital Elevation Models (DEM) do enable the development of non-invasive detailed investigation of virtually *each and every* ancient agricultural terraced field in the Negev. An earlier GIS-based hydrological model, developed by the third author (Svoray, 2004), was applied to assess runoff contribution at Horvat Benayah, a semi-arid area with wadi terraces south of Hebron (Ackermann et al., 2008).

We have further developed the Svoray (2004) and Ackermann et al. (2008) models, coupled with the D-Infinity (Tau DEM) algorithm (Tarboton, 1997), to assess runoff yields at the rural archaeological site of Horvat Haluqim in the central Negev desert, near Kibbutz Sede Boker (Fig. 1). The Terraced Wadi System, which has not been investigated so far in terms of runoff yields by individual terraced fields, is present at this site. Here we show results of model-calculated runoff overland flow yields in 13 ancient terraced fields at Horvat Haluqim during an average year (1989–90) with 88 mm precipitation, a very wet year (1991–92) with 188 mm, and a severe drought year (1999–2000) with only 34 mm rainfall.

Dealing with ancient agriculture in the central Negev Highlands, a concise background is given of palaeoclimate during the Holocene and the range of climatic fluctuations, also including modern times. The past climate in the southern Levant during the Holocene is reflected by lake level changes of the Dead Sea, which can be considered as a large regional rain gauge.

The largest ephemeral stream in the central Negev Highlands, Nahal Zin, having a catchment of 1400 km^2, flows to the Dead Sea (Fig. 1). The palaeo-hydrology of Nahal Zin was investigated by Greenbaum et al. (2000) along a canyon near the Arava valley (Fig. 1), based on slackwater deposits and other sedimentary indicators. The authors also studied the occurrence of floods in Nahal Zin during modern times in relation to instrumental and historical records. They presented evidence of 28 large floods in Nahal Zin during the past 2000 years, ranging in magnitude from 200 to 1500 m^3 per second. A good correlation exists between high Dead Sea levels, indicating a comparatively wetter climate, and a high frequency of large flood events during the period 620–1120 CE and during the modern period 1940–2000. Periods with low flood frequency (270–620 CE and 1120–1940 CE) correlate with low Dead Sea levels, indicating a drier climate. The authors also note that the period 1120–1470 CE is characterised by a small number of very large floods. The respective effects of either Mediterranean or Red Sea meteorological depression systems on the Nahal Zin catchment are factors to be considered. Modern instrumental data available since 1935 show a positive relation between Dead Sea levels and rainfall amounts, the number of floods, as well as flood magnitudes (Greenbaum et al., 2000).

Lake levels of the Dead Sea during the past 4000 years fluctuated mostly within the range of −390 to −415 m below the level of the Mediterranean Sea according to research by Bookman et al. (2004). Other studies include an exceptional high lake level of −372 m, dated by radiocarbon to 3330 ± 50 BP (Bartov, 2004; Kagan et al., 2015). Pollen investigations of Dead Sea sediments (Litt et al., 2012), also dated by radiocarbon, suggest that the southern Levant was comparatively dry and warm during the early Holocene (ca 10 000–6.500 cal BP), wetter and colder during the mid-Holocene (6300–3300 cal BP), becoming again drier and warmer during the late Holocene (ca 3200 cal BP to present).

Speleothem records with a high-resolution of 3–20 yr from the Soreq Cave in the semi-arid to sub-humid zone of central Israel indicate rainfall changes between about 300 and 700 mm for that area during

Table 1
Altitude, rainfall, temperature, P/PET index, and P/PET climate of 6 meteorological stations in the Negev (Fig. 1), showing the average values for the decade 1990–2000, the annual values for the very wet year 1991–92, and for the severe drought year 1998–99 (based on Bruins, 2012).

Meteoro-logical Station	Alt.	Decadal Average 1990–2000				Wet year 1991–92				Drought year 1998–99			
	m	Rain mm	Temp °C	P/PET index	P/PET climate	Rain mm	Temp °C	P/PET index	P/PET climate	Rain mm	Temp °C	P/PET index	P/PET climate
Beer Sheva	280	188.8	20.1	0.13	Arid	280.5	18.7	0.20	Semi-arid	63.9	21.0	0.04	Hyper-arid
Arad	605	124.4	19.2	0.09	Arid	173.3	17.6	0.13	Arid	50.8	20.1	0.03	Hyper-arid
Sede Hayil	310	87.6	19.3	0.06	Arid	143.7	18.2	0.10	Arid	35.4	19.9	0.02	Hyper-arid
Sede Boker	470	93.3	18.4	0.07	Arid	187.8	17.3	0.14	Arid	34.0	19.0	0.02	Hyper-arid
Yotvata	80	28.5	23.1	0.01	Hyper-Arid	22.5	21.7	0.01	Hyper-Arid	32.6	23.8	0.01	Hyper-Arid
Eilat	11	23.7	25.1	0.01	Hyper-Arid	17.1	24.0	0.01	Hyper-Arid	24.9	25.7	0.01	Hyper-Arid

the Mid-Holocene (Bar-Matthews and Ayalon, 2011). They found evidence for comparatively dry periods during 4650–4600 BCE, 4250–4180 BCE, 3700–3600 BCE, 3250–3170 BCE and 2200–2050 BCE. On the other hand comparatively wet periods occurred during 4700–4680 BCE, 4170–4100 BCE, 3760–3740 BCE and 3500–3450 BCE. Such a high resolution is quite rare for proxy palaeoclimatic indicators. Fuks et al. (2017) found evidence for both drought years and wet years during the Byzantine period.

Detailed annual climatic changes are available only from modern instrumental meteorological data, which were studied by Bruins (2012) for southern Israel, including the entire Negev region (Table 1). The conventional annual time boundary (January 1 – December 31) cuts the rainy season and related agricultural season in Israel (and the Levant) in the middle. Therefore, a rainfall year of 12 months in Israel is usually taken from September 1 to August 31, to include all rainfall events during the entire rainy season and agricultural year.

Annual differences in rainfall in the central Negev Highlands range from 34 mm during severe drought years (1998–99, 1999–2000) to 188 mm during very wet years (1991–92). There was not a single year with a semi-arid climate in the central Negev Highlands since the availability of instrumental meteorological data. Even during 1991–92 (Table 1), the wettest year ever recorded in Israel since the beginning of rainfall data collection in the mid-19th century, the semi-arid zone did not move southward into the central Negev, which remained arid (Bruins, 2012). The variability of the *average* climate, say for periods of 30 years, will show much less change in terms of rainfall amounts than the *annual* variations. Proxy palaeoclimatic indicators usually reflect a multi-year average. Given the range of Holocene lake level variations in the Dead Sea (Bookman et al., 2004), as compared to Dead Sea levels during the 19th and 20th centuries, before water pumping from the Jordan river system artificially lowered the lake level, it seems that the central Negev was dominated by an arid climate in general and a hyper-arid climate during drought years.

In fact, during severe drought years, such as 1998–1999 and 1999–2000, the hyper-arid zone, usually restricted to the southern Negev and the Arava Rift Valley (Fig. 1), penetrated not only into the central Negev, but also into the northern Negev, while most of Israel was covered by the arid zone. Hence during a severe drought year, almost the entire country of Israel is under a desert climate (Kafle and Bruins, 2009).

In conclusion, the above proxy palaeoclimatic indicators and modern instrumental data of annual climatic fluctuations suggest that climatic conditions in the central Negev were usually arid during average rainfall years and wet years, but hyper-arid during drought years. Therefore, additional runoff water in the region was necessary to enable agriculture during different archaeological periods (Bruins, 2012). Moreover, farming by a settled population in the central Negev desert is not necessarily related to wetter climatic periods. Political and human factors also played an important role that determined permanent settlement and runoff farming, even during comparatively dry phases such as the Byzantine and Early Islamic periods (Bruins, 1994; Avni et al., 2013; Fuks et al., 2017).

2. Objectives and methodology

As aforementioned, it is difficult to investigate each and every ancient agricultural field in the Negev desert with hydrographs, conventional hydrological fieldwork and agricultural field trials. The remarkable development of GIS and DEMs during the past decades enables new research methodologies that facilitate non-invasive detailed investigation of *each* ancient agricultural system and terraced field in the Negev.

We focus here on a 1st order terraced wadi at the rural archaeological site of Horvat Haluqim (Cohen, 1976; Bruins et al., 1986; Bruins and Ore, 2008; Bruins et al., 2012; Bruins and Van der Plicht, 2017a, 2017b), located 1.7 km north-east of Kibbutz Sede Boker in the central Negev desert (Figs. 1 and 2). Agricultural fields in Terraced Wadi Systems of low order stream channels are situated in the upper reaches of the watershed (Fig. 2). Therefore, the terraced wadi fields receive mainly runoff water from the adjacent hillslopes as overland flow. Most rainfall events in the region are in the range of 3–10 mm (Sharon, 1972; Evenari et al., 1982). Such mild to moderate rainfalls in the small watersheds at Horvat Haluqim cause overland flow along the hillslopes, being about 40–80 m in length, as witnessed by the first author during various rainfall events. Even if channel flow develops in the wadi bed (floodwater), the flows are gentle.

A nearby modern terraced wadi system (1st order stream channel), built by the Jewish National Fund to establish trees in the desert, shows water from runoff overland flow, captured by stone terrace walls in individual terraced fields, next to Horvat Haluqim (Figs. 2 and 3).

Measuring the respective runoff amount *received by each individual terraced field* seems rather complicated in the Terraced Wadi System, because it is difficult to gauge overland flow. It would require substantial artificial landscape changes at the bottom of each hillslope, just above each terraced field, to concentrate the overland flow into one point where the runoff amount can be measured with a hydrograph. Hence it is no surprise that the Terraced Wadi System in the Negev has so far not been investigated in terms of runoff amounts received by individual terraced fields. For example, investigating runoff yields by each of the 13 terraced fields of the eastern wadi at Horvat Haluqim by conventional hydrology would require 26 landscape changes along the lowermost part of the slope just above each field and installation of 26 hydrographs, so that the overland flow from the two opposite slope sections can be measured (Figs. 3 and 4).

A detailed DEM of the three terraced wadis and their hillslope catchment areas at Horvat Haluqim was carefully constructed, using high resolution airborne LiDAR data. The resulting DEM, having a high resolution of 0.5 m, was integrated with the Ackermann et al. (2008) model. In addition, multiple water flow directions were evaluated here, using the D-Infinity (Tau DEM) algorithm (Tarboton, 1997). This algorithm calculates the flow direction as a single angle on a block-centred grid, determining the steepest downward slope on planar

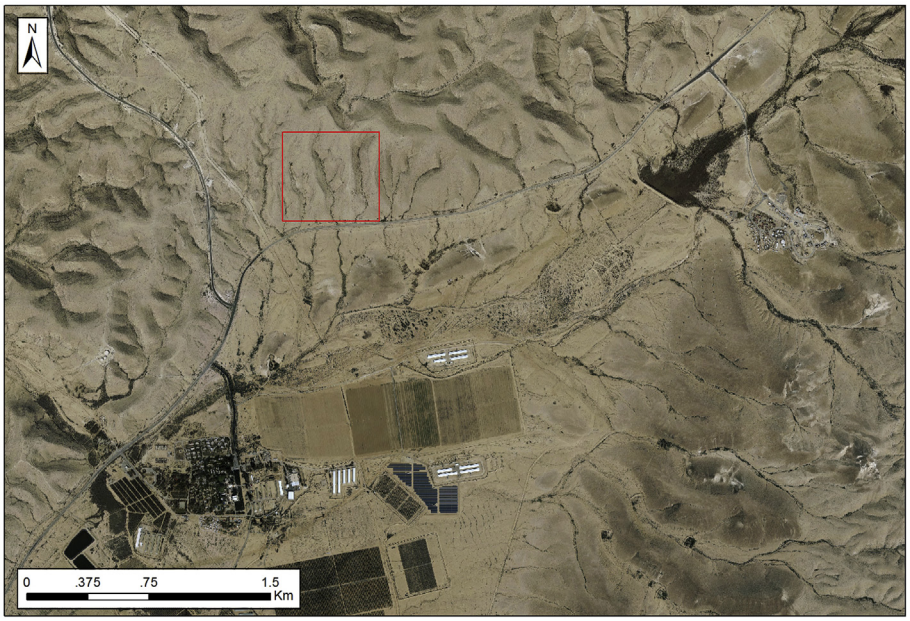

Fig. 2. The rural archaeological site of Horvat Haluqim, situated on the Haluqim Anticline, is marked by a rectangle, showing three parallel wadis that were terraced in ancient times. Road 40 is visible west (left) of the rectangle, along which modern terraced wadis were established by the Jewish National Fund to plant and grow trees in the desert. The houses of Kibbutz Sede Boker and its large agricultural fields are visible in the Synclinal Valley (Orthophoto © Survey of Israel).

triangular facets. Based on the flow direction output, the runoff contributing area of each hillslope was precisely calculated (grid cells) for each individual terraced field (Fig. 5).

Model predictions are presented for the 13 ancient terraced fields of the eastern wadi of Horvat Haluqim (Fig. 2). Though the runoff contributing area of each terraced field can be calculated accurately with our model, the issue of runoff computation is more complex. The model represents a simplification of the real world, which is very multifaceted as described by Emmett (1970:A1): "*Overland flow is both unsteady and spatially varied since it is supplied by rain and depleted by infiltration, neither of which is necessarily constant with respect to time and location*". The actual amount of runoff cannot be determined accurately by the model, due to various complicating factors evaluated in the following section in relation to runoff coefficients. Therefore, the runoff yields calculated by our model are to be viewed as an approximation. Nevertheless, such an approximation can still give meaningful results, approaching but not reaching absolute reality.

The runoff coefficient, i.e. the amount of runoff as a percentage of the amount of rainfall, is critical in the model calculation results. The amount of runoff that reaches a specific terraced field from a contributing catchment depends on a number of factors, including rainfall duration, rainfall intensity, catchment size, hillslope length, geomorphic surface characteristics, infiltration, etc.

We took for our runoff yield calculations a simplified annual approach, disregarding individual rainfall events and using an average annual runoff coefficient of 10%, i.e. an annual rainfall amount of 100 mm will contribute 10 mm runoff to the terraced wadi fields. This figure is rather conservative and is partly based on the comprehensive hydrological research conducted by Shanan (1975, 2000) at the reconstructed Avdat Farm (Shanan and Schick, 1980; Evenari et al.,

Fig. 3. A modern terraced wadi with stone terrace walls, built by the Jewish National Fund to enable tree growth in the otherwise treeless desert. Notice that the landscape surface is dominated by loess soil and rock fragments overlying hard limestone of the Turonian Nezer Formation. The runoff water captured by the terrace walls is still visible one day after the rainfall event, due to the low infiltration rate into the alluvial loess soil. The rural archaeological site of Horvat Haluqim, situated a few hundred metres to the north-east, has three ancient terraced wadis similar as the modern one in the foreground. Road 204 from Kibbutz Sede Boker to Yeruham is visible in the background. (Photo by H.J. Bruins, 19-01-2010).

Fig. 4. Part of the terraced eastern wadi of Horvat Haluqim. Stone terrace wall 10 is clearly visible. Notice the runoff overland flow, which gives a shiny gloss in parts of the picture, both on the concave hillslopes and on the loess soil surface of the terraced fields in the foreground. An erosion channel is visible to the right, in which gentle channel flow occurs (Photo by H.J. Bruins, 07-04-2013).

Fig. 5. Our model can determine the runoff contributing area (highlighted in dark grey) within the natural landscape for each terraced wadi field at Horvat Haluqim. Thus we calculated the number of cells, as indicated in the legend, which contribute to each terraced field, according to flow direction. Notice that the overland flow length along the hillslopes at Horvat Haluqim is in the range of ~40–80 m.

1982), located 11.8 km south of Horvat Haluqim, and also partly based on the hydrological research by Yair et al. (1980) of an instrumented slope section (Lavee and Yair, 1990; Yair and Kossovsky, 2002; Yair and Raz-Yassif, 2004) at the Haluqim Anticline, 3.8 km south-west of Horvat Haluqim. However, unlike the research at the Avdat Farm, the latter hydrological investigations did not focus on runoff amounts received by terraced agricultural fields.

3. Runoff coefficients in the central Negev desert

We evaluated runoff coefficients measured by hydrological research in the central Negev region and the factors involved. Such an evaluation is necessary to present the rational concerning our selection of an average annual runoff coefficient of 10% for our preliminary model calculations in our study of the eastern terraced wadi at Horvat Haluqim.

3.1. Average annual runoff coefficients measured in relation to reconstructed ancient farms or cisterns

The only combined hydrological and agronomic research in the Negev Highlands to investigate the functioning of ancient farming systems based on runoff and floodwater was conducted by Evenari et al. (1982). They restored in 1958 an ancient terraced wadi with hillside conduits near the Byzantine town of Shivta (Fig. 1). A few years later, in 1960, they restored another ancient Byzantine farm near the town of Avdat (Fig. 1). Both farming systems are characterised by a series of hillside conduits, which collect runoff from the adjacent hillslopes (Fig. 6).

Their hydrological investigations included detailed rainfall and runoff/floodwater measurements from 1960 to 1967, besides related agronomic investigations that continued into the 1980s. Shanan established an evaporation pan, 14 rain gauges to measure precipitation amounts/intensities and 8 automatic hydrographs with V-notch weirs (Fig. 6) to measure runoff volumes and flow rates at each outflow point of a conduit channel or natural stream channel into the terraced agricultural fields (Shanan, 1975, 2000; Shanan and Schick, 1980; Evenari et al., 1982). The rather ingenious Hillside Conduit System was apparently developed and built during the Byzantine period, probably in conjunction with the growth of perennial grapevines and industrial wine production (Rubin, 1991; Erez Edelson, 2004). Grapevines are small trees that require more water than seasonal field crops like wheat and barley.

The extensive and systematic research by Shanan (Table 2) of runoff from various different watershed sizes highlights the effect of catchment size on runoff coefficient (Table 2): the smaller the catchment area, the larger the runoff coefficient (Shanan and Schick, 1980; Shanan, 2000; Evenari et al., 1982).

Concerning the southern catchment of the Avdat Farm, five hillside conduits (Fig. 6: conduits 3, 4, 5, 6 and 7) artificially subdivide the eastern hillslopes into smaller sub-catchments. The eastern hillslopes at the Avdat Farm have a considerable length of about 340 m–215 m, measured from the nearby hilltops in the east (Fig. 6) to the terraced fields or to the natural streambed in the southern valley. Rock outcrops (chalk and limestone, mostly of the Eocene Horsha Formation) occasionally appear along the upper slopes, but loess soil and stones (rock fragments) usually cover the Horsha Formation along the upper, middle and lower parts of the slopes. All loessial soils in the central Negev region are covered by a crust, about 2–4 mm thick (Shanan and Schick, 1980; Evenari et al., 1982). The closely spaced conduit channels in the middle part of the eastern hillslope considerably shortened the length of slowly moving overland flow, converting the runoff into channel flow. Thus less runoff water was lost on the long hillslopes, due to infiltration. Consequently, more water, also from the upper and middle part of the long slopes, could reach the terraced agricultural fields (Shanan, 1975, 2000; Shanan and Schick, 1980; Evenari et al., 1982).

The south-western hillslopes of the southern catchment of the Avdat Farm (Fig. 6) are both lower and shorter, covered by crusted loess soil

Fig. 6. Looking southward from the Byzantine City of Avdat, the reconstructed ancient Avdat farm is visible, an example of the Hillside Conduit System. Notice that most of the hillslopes are covered by crusted loess soil and stones; bare bedrock exposures are rare. Hydrographs 1, 2, 3, 4, 5, 6 and 7 measured the runoff channel flow of the respective hillside conduits (except 2, which measured the channel flow in the natural southern wadi bed). The hillside conduits, visible on the hillslopes, drain catchments ranging in size from 1 to 7 ha. Their average annual runoff coefficient is 8.9% (Shanan and Schick, 1980; Evenari et al., 1982:145). Perennial grapevines were apparently grown in these systems; an ancient winepress is visible in the foreground. Hydrograph 8 measured the runoff/floodwater contributed by a large wadi, fed by a catchment of 345 ha. The average annual runoff coefficient of this large catchment is only 2.8% (Photo H.J. Bruins, 29-03-2013).

and stones, overlying the Horsha Formation. One hillside conduit is situated here (Fig. 6: conduit 1). Hydrograph 2 measured the flow in the natural streambed of the southern wadi. The length of the hillside conduits ranges from 930 m (conduit 1) to only 80 m (conduit 3). The latter conduit has the lowest average annual runoff coefficient of 5.0% (Table 2). Interestingly, the highest average runoff coefficients are from the low southwestern hill spur (conduit 1) and from the natural southern wadi streambed (hydrograph 2), respectively 11.4% and 12.2%. It is important to emphasize that hardly any rock outcrops occur along the southwestern hill spur, while geomorphic surfaces composed of loess soil and loess mixed with stones (rock fragments) dominate. Nevertheless, runoff yields are higher than from the eastern slopes, which have more bedrock outcrops.

Though the importance of rock outcrops on runoff production has been underlined by Yair et al. in their investigations (Yair et al., 1980; Lavee and Yair, 1990; Yair and Kossovsky, 2002; Yair and Raz-Yassif, 2004), and also by Wieler et al. (2016), the runoff contribution of crusted loess soils should not be underestimated, as shown by the studies by Shanan (Table 2). Evaluation of system design with respect to runoff collection in ancient farming systems and cisterns for drinking water in the central Negev desert show that both loess covered slope sections and bedrock dominated slope sections were utilized to harvest runoff water (Bruins and Ore, 2008).

The effect of surface stoniness of loess soils on runoff production in the region was first investigated by Shanan, who established 20 runoff plots, each one 4 m wide and 20 m long (80 m^2 or 0.008 ha) on the lower western hillslope above the terraced fields at the Avdat Farm (Shanan and Schick, 1980; Evenari et al., 1982). Most plots were cleared of stones in order to investigate differences in runoff production between rather clean loess surfaces and geomorphic surfaces having a natural mixture of loess soil and stones. The results showed that smooth loess soil produced more runoff than loess with stone cover for rainfalls of less than 10–12 mm/day. However, the reverse was found for rainfalls greater than 15 mm/day. The former type is more frequent in the region, as investigated by Sharon (1972), who found that light rains of less than 8 mm/h constitute the major portion of the rainfall events in the Negev Highlands.

These results prove that ancient stone clearance was carried out in the past to increase runoff water harvesting from hillslopes (Shanan and Schick, 1980). The resulting formation of stone mounds (Tuleilat el-Anab, grape mounds in Arabic) is an accompanying disposal waste product of stone clearance. Subsequent hydrological research by Lavee et al. (1997) further confirmed and refined these conclusions regarding ancient stone clearance from loess soil surfaces. Their hydrological research revealed a novel aspect. Stones largely embedded in the soil increased runoff and were not removed by the ancient farmers, but only

Table 2
Catchment sizes of hydrological measurements at the reconstructed Avdat Farm and the reconstructed Shivta cistern, showing average annual rainfall, runoff and runoff coefficients for the period 1960–1967 (based on Evenari et al., 1982:139–147).

	Catchment Area (ha)	Average Annual Rainfall (mm)	Average Annual Runoff (mm)	Average Annual Runoff Coefficient (%)
Avdat Hillside Conduit 1	7.0	86.6	9.9	11.4
Avdat Southern Wadi Bed (Conduit 2)	5.4	86.6	10.6	12.2
Avdat (Hydrograph 3)	5.5	86.6	4.3	5.0
Avdat Hillside Conduit 4	3.1	86.6	5.3	6.1
Avdat Hillside Conduit 5	1.0	86.6	9.5	11.0
Avdat Hillside Conduit 6	3.7	86.6	6.5	7.5
Avdat Hillside Conduit 7	4.3	86.6	7.6	8.8
Avdat Eastern Wadi Bed (Hydrograph 8)	345.0	86.6	2.4	2.8
Avdat runoff plots (80 m^2)	0.008	86.6	22.0	25.4
Shivta cistern	1.2	93.0	12.0	12.9

those stones that rested on the soil surface. "*This selective removal increased the volume of runoff generated over one square meter by almost 250% for small rainfall events compared to natural untreated soil surfaces*" (Lavee et al., 1997:341).

Ancient stone mounds on the lower slopes of Har Eldad, a large table mount situated to the southwest of the ancient city of Avdat, were investigated by Bruins and Ore (2008). They measured the spacing and size of the stone mounds (Tuleilat el-Anab): "*The largest mounds occur at the upper part of the colluvial slope, apparently because stone cover and stone size there was larger than at the lower part of the colluvial slope, while the grid-size of stone clearance was uniform, ca. 180 m^2* per *stone mound*" (Bruins and Ore, 2008:241). This result proves that each stone mound is a waste disposal product of stone clearance. The stone mounds have no function in themselves and cover only a small area of a few square metres, whilst a smooth loess surface is obtained of about 180 m^2, containing only embedded stones. Thus significantly more runoff was obtained from these loess covered slopes.

The stone-cleared runoff plots of 80 m^2 studied by Shanan on the lower western hillslope of the Avdat Farm (Shanan and Schick, 1980; Evenari et al., 1982; Shanan, 2000) have an overland flow length of 20 m and a surface of crusted loess soil. Their average annual runoff coefficient was measured to be 25.4% (Table 2).

A catchment of 1.2 ha in the Shivta area (Fig. 1) was used to harvest runoff water into a cistern. The geological substratum of the watershed is chalk and limestone of the Santonian Menuha Formation, largely covered by loess and stones. Ancient stone mounds are visible in this watershed, showing that stone clearance was carried out in the past to obtain more runoff, guided by a conduit channel into the cistern. The average annual runoff coefficient was measured to be 12.9% (Table 2; Evenari et al., 1982).

Stone clearance was not carried out in the southern catchment of the Avdat Farm, subdivided by conduit channels into watersheds of 1.0–7.0 ha, having average annual runoff coefficients in the range of 5%–12.2%.

Finally, the large eastern catchment of 345 ha near the Avdat Farm, characterised by a mixture of hillslope surfaces, without stone clearance, and 1st to 3rd order terraced wadis with erosion channels, was measured to have an average annual runoff coefficient of only 2.8% (Table 2; Shanan and Schick, 1980; Evenari et al., 1982). Indeed, the larger the catchment area, the lower the runoff coefficient.

3.2. Runoff coefficients measured at a slope section of the Haluqim Anticline

Detailed hydro-geomorphological research was conducted by Yair et al. (1980) along an instrumented slope-section of the Haluqim Anticline west of Kibbutz Sede Boqer. The objectives of their investigations were clearly stated: "*the study of spatial variations in rainfall, runoff and erosion processes along slopes*" (Yair et al., 1980:243). Ancient agricultural terraced wadi fields were not included in their investigations and data collection. The studied part of the hillslope covers an area of 11 325 m^2 (1.1 ha), in which a network of 19 rain gauges was established, as well as an evaporation pan, a number of volumetric water meters, water level recorders and suspended sediment samplers.

The investigated slope section includes three geological formations (Fig. 7) of the Turonian period (Arkin and Braun, 1965). The Nezer Formation, composed of well-bedded hard limestone, makes up the upper part of the hillslope and its geomorphic surface is characterised by alternating strips of bedrock exposure and loess soil/stone cover. The middle part of the hillslope is composed of the Shivta Formation, showing a geomorphic surface of massive oolitic calcarenite limestone, generally devoid of soil cover. The Drorim Formation, situated at the lower part of the hillslope, consists of limestone, chalk and marl, but bedrock outcrops are limited and the geomorphic surface is largely composed of colluvial deposits of loess soil and stones (Yair et al., 1980; Lavee and Yair, 1990).

Unlike the hydrological research by Shanan at the reconstructed ancient farms near Shivta and Avdat, described above, the hydrological research by Yair et al. was not focused on runoff yields by ancient agricultural fields or cisterns. The hillslope section (Fig. 7) was divided for runoff measurements in the following manner Yair et al. (1980): "*The study of the spatial variations in slope runoff is based on 10 contiguous plots draining parallel strips of the entire experimental site. Three of these plots numbered 2, 4 and 9 were subdivided into three subplots each: a long one, extending from the divide to the slope base and the two adjoining ones short, draining the upper or lower section of the slope respectively*". Slope length of the studied plots varies from 55 to 76 m and slope gradient from 12 to 29.5% (Lavee and Yair, 1990).

Average annual runoff coefficients of the studied slope sections on the Haluqim Anticline were unfortunately not published. However, individual runoff coefficients were presented of three specific rainfall events. A medium type of rainstorm occurred during 25–27 December 1988 (Yair and Raz-Yassif, 2004). It gave 12.2 mm precipitation in the sub-catchment drained by the Upper Channel and 13.7 mm precipitation in the sub-catchment drained by the Lower Channel. The distance between the hydrometric stations of the Upper and the Lower Channel is 200 m.

Concerning the location and size of the sub-catchments, as well as the position of the hydrometric stations, the authors write (Yair and Raz-Yassif, 2004:157): "*The first (named Upper Channel) is located at the transition from the headwater rocky area into the alluvial reach of a first-order drainage basin and drains 0.*8 ha. *The convergent slopes are short, and very extensive rocky outcrops, almost devoid of soil and vegetation cover, form most of the surface. The second (Lower Channel) is located at the mouth of the same drainage basin and drains 2.*1 ha. *The valley side slopes are long and soil cover is more extensive. It is characterised by soil strips at the base of rock steps at the upper rocky slope sections and a colluvial mantle at the base of long slopes*".

The geological formations, however, are not mentioned. It seems that the Upper Channel drains only the Nezer and Shivta Formations, while the Lower Channel drains also the colluvial slope overlying the Drorim Formation. Anyhow, the runoff coefficient of the Upper Channel is 28% and of the Lower Channel only 3.8% (Yair and Raz-Yassif, 2004:161). The authors concluded that most runoff produced by the Lower Channel sub-catchment rocky upper slope infiltrated into the lower colluvial slope. Thus little runoff reached the hydrometric station at the base of the colluvial slope, resulting in a runoff coefficient of merely 3.8% in a catchment of only 2.1 ha, compared to 28% for the hydrometric station at the base of the headwater rocky area of the slope with a catchment of 0.8 ha.

An extensive regional rainstorm covered most of the Negev desert during March 22–23, 1991. The event lasted for 36 h and consisted of three major spells, (Yair and Kossovsky, 2002). The amount of precipitation was 45.6 mm, being about half of the average annual total in the Haluqim – Sede Boqer area. A rainfall event of such magnitude is rare and may occur once every 10 years. The runoff coefficients during this event were 65% in the Upper Channel and 37% in the Lower Channel (Yair and Kossovsky, 2002). Such a large rainstorm caused a tenfold increase in the runoff coefficient at the base of the colluvial slope (Lower Channel) and more than doubled the runoff coefficient for the rocky upper slope (Upper Channel), as compared to the 13 mm rainfall event of 25–27 December 1988.

The highest recorded rainfall episode occurred during January 1–3, 1992, which gave 53.2 mm of precipitation (Yair and Kossovsky, 2002). Such a rainfall is truly exceptional and took place during the wettest year ever recorded in Israel, 1991–92, since the beginning of precipitation measurements in the middle of the 19th century. The runoff coefficient was 52.7% in the upper channel and 28% in the lower channel (Yair and Kossovsky, 2002). These figures are slightly lower than in the previous case, but in the same order of magnitude. Such large rainfall events are indeed very rare in the region and cannot be used as a standard in relation to runoff yields for ancient agricultural

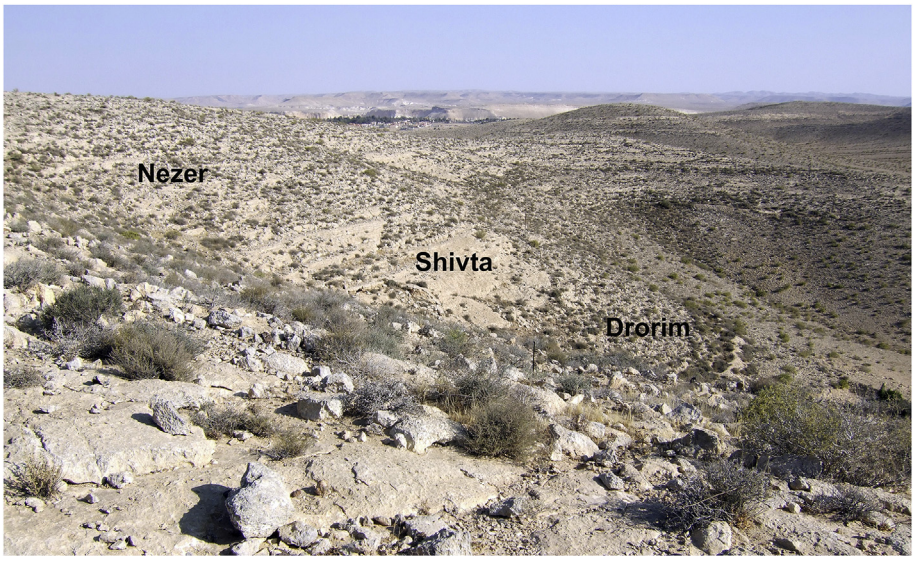

Fig. 7. Instrumented slope section on the Haluqim Anticline, established by Yair et al. (1980). Three geological formations of the Turonian period form the geological substratum along the studied hillslope section: Nezer, Shivta and Drorim. The massive Shivta Formation is visible as a distinct bedrock outcrop, but the well-bedded Nezer Formation shows alternating strips of rock outcrops and strips of loess soil mixed with stones. The Drorim Formation is largely covered by colluvium. Looking at the surface of the entire slope length, it is clear that loess soil and stones dominate in areal extent over bare bedrock outcrops. The slope section lies about 3.8 km south-west of Horvat Haluqim (Photo H.J. Bruins, 01-05-2008).

systems in the central Negev desert, as light rains (less than 8 mm/h) dominate in the Negev Highlands (Sharon, 1972).

3.3. Geotechnical runoff coefficients of bedrock sample blocks, as well as the importance of crusted loess soils

Novel measurements to determine geotechnical runoff coefficients of bedrock types in the central Negev region were carried out by Wieler et al. (2016). These runoff coefficients were measured in the lab on small bedrock samples (blocks), having a volume of 1000 cm^3. It is clear that the resulting runoff is from a very small surface area, as the bedrock blocks appear to be about 10 × 15 × 7 cm in size. Nevertheless the results obtained by Wieler et al. (2016) give a useful parameter to compare the inherent runoff contributing capacity of various geological formations present in the central Negev desert. The authors also made a useful analysis with GIS of stream order in which ancient agricultural fields are situated within an area of 160 km^2 west of Kibbutz Sede Boker (Wieler et al., 2016:157).

However, their approach to calculate runoff coefficients of the various drainage basins, based only on the geological formations involved, seems not realistic in relation to the ancient agricultural fields. The authors did not include in their investigation the presence of loess soil, which is the predominant and practically omnipresent feature of the hilly landscape in the central Negev Highlands. The bedrock of many geological formations in the catchments of ancient farming fields is often not exposed but covered by loess soil, usually mixed with stones, as shown for the Shivta Farm (Fig. 8). The geological substratum of the Shivta Farm (Table 3), as indicated by the geological map of Shivta (Sneh et al., 2011), does not necessarily reflect the type of the actual geomorphic surface on which runoff develops. Therefore, runoff calculations only based on bedrock runoff potential ignore a significant part of the geomorphic surface reality, i.e. bedrock covered by loess.

A second misunderstanding is stated by the authors as follows (Wieler et al., 2016:156): "*Runoff coefficient for the loessic soil was not dealt with in this work since we simulated only light rains; runoff thresholds for the loessic soil are higher than for bedrock (Yair, 1983), therefore, no parameters were defined for the loessic soil*". Their perception, citing Yair (1983), that light rains do not produce runoff on loess soil is erroneous. The extensive multi-year hydrological research by Shanan (1975) at the reconstructed Avdat Farm showed beyond any doubt that light rains above 3 mm do produce runoff on loess covered slopes, see also Shanan and Schick (1980) and Evenari et al. (1982). The crust on the loess soil absorbs about 2.5–3 mm of rainfall, but then the crust is saturated and, if the rain continues, runoff will suddenly appear as a shining film of water on the loess surface, subsequently flowing down as runoff overland flow. This process has been witnessed repeatedly by the first author (Bruins), who has lived for more than three decades in the central Negev Highlands.

The significance of crusted loess soil in the region for ancient agriculture is clearly written by Evenari et al. (1982:109): "*… most of the rainfall of the region falls in relatively light showers of 3 to 10 mm at a time. Now the loess soils typical of this region … form a characteristic crust when wet. This crust soon becomes impermeable to rain and therefore there is runoff even with light rains … It was this character of the loess soils that enabled the ancient farmers to harvest water from the hillsides even under these low-rainfall desert conditions*".

The loess soils in the region are derived from dust deposition, settling like snow on the entire landscape surface during dust storms. The phenomenon of dust storms was not limited to the Late Pleistocene but continued also during the Holocene. Each year quite a number of dust storms occur in the Negev desert (Offer and Goossens, 2001), depositing dust that becomes loessial (silt-loam) soil with a crust.

For example, concerning the Avdat Farm watershed, the geological substratum is composed mainly of chalk of the Eocene Horsha Formation (geotechnical runoff coefficient 48%, Wieler et al., 2016) and only for a small part by limestone of the Eocene Matred Formation (geotechnical runoff coefficient 87%, Wieler et al., 2016). We carried out supervised land cover classification for the Avdat Farm catchment, using an orthophoto image from the Survey of Israel and Erdas Imagine. The results show that only 3% of the watershed surface is composed of bedrock outcrops, whilst 93% is covered by loess soil (partly mixed with stones), and 4% is covered by vegetation. Therefore, using bedrock runoff coefficients of the geological substratum as a basis for calculating the runoff coefficient of a drainage basin (Wieler et al., 2016:157), but ignoring the predominant loess cover is unrealistic.

Finally, estimating the runoff coefficient of an entire drainage basin is certainly legitimate in itself. But such an approach is perhaps less useful in relation to ancient agricultural fields situated in the streambed. The 46 drainage basins involved in their study range in size from 53 ha to 5428 ha (Wieler et al., 2016:157).

For comparison, the southern watershed of the Avdat Farm has a size of 30 ha, but the sub-catchments with conduit channels range in size from 1 to 7 ha (Shanan and Schick, 1980). The average annual runoff coefficient of these smaller sub-catchments is in the range of 5.0–12.2% (Table 2). The large eastern watershed of the Avdat Farm has a size of 345 ha with an average annual runoff coefficient of only 2.8%, as measured by Hydrograph 8 (Fig. 6).

Past agricultural reality was even more intricate: the eastern

Fig. 8. The ancient Shivta Farm reconstructed in 1958 by Evenari et al. (1982). Many fruit trees are still alive, even though there has hardly been any maintenance during the past decades. This fact underlines the hydrological viability of farming based on runoff/floodwater capturing in the area under present climatic conditions that also include severe drought years. Crusted loess soil mixed with stones covers the geological substratum of the Turonian Nezer Formation. The ancient farmers were active in stone clearance on the loess-covered hillslopes, as shown by many stone mounds in the catchments with conduit channels. This fact underlines the significance of loess-covered hillslopes in runoff production for the terraced agricultural fields at the Shivta Farm (Photo by H.J. Bruins, 31-03-2014).

watershed contains 18 first order and 3 second order basins, in which many terraced fields are situated that cover a cultivable area of about 12 ha (Shanan and Schick, 1980:271; Evenari et al., 1982:143). These terraced fields, through which modern erosion channels drain most floodwater, were not reconstructed. If the stone terrace walls would have been rebuilt and the erosion channels filled up, most runoff water generated by the hillslopes of the eastern catchment would have been captured by these terraced fields. Then Hydrograph 8 would have received much less floodwater at its point of measurement in ancient times.

Therefore, it seems more useful, from the perspective of agriculture and farming, to assess the specific catchment area of each individual terraced field. This is the approach we took in our modelling study of a terraced wadi at Horvat Haluqim.

4. GIS-based hydrological model of terraced Wadi fields at Horvat Haluqim

4.1. Average annual runoff coefficient: approximation rational

Our rational for approximating an average annual runoff coefficient of 10% for the terraced wadi fields at Horvat Haluqim is based on the instrumented hydrological records of the Avdat Farm (Shanan and Schick, 1980; Evenari et al., 1982; Shanan, 2000) and the Haluqim slope section (Yair et al., 1980; Lavee and Yair, 1990; Yair and Kossovsky, 2002; Yair and Raz-Yassif, 2004).

The eastern wadi at Horvat Haluqim is a 1st order stream channel (Figs. 2 and 9), in which 13 ancient terraced fields can be observed, according to the number of visible terrace wall remains (Fig. 4). It is a rural archaeological site and neither the terrace walls nor the related terraced fields have been restored. The geological substratum at Horvat Haluqim is the Turonian Nezer Formation (Table 3), which also makes up the upper part of the investigated Haluqim slope section, investigated by Yair et al. (1980). Alternating strips of bedded rock outcrops and strips of loess soil mixed with stones characterize the hillslopes of the Nezer Formation, both at Horvat Haluqim (Fig. 9) and at the instrumented upper slope section of the Haluqim Anticline (Fig. 7).

However, the Shivta and Drorim Formations, situated along the middle and lower part of the latter slope section, are *not* exposed in the eastern wadi catchment of Horvat Haluqim. Moreover, there is *no colluvium* at the lower hillslopes at Horvat Haluim, as hard limestone bedrock outcrop layers (Nezer Formation) appear also at the bottom of the hillslope just above the terraced wadi bed (Fig. 10). The latter aspect is an important advantage in terms of runoff overland flow. The length of the studied instrumented slope sections at the Haluqim Anticline varies from 55 to 76 m (Lavee and Yair, 1990), which is rather similar as the slope length at Horvat Haluqim (40–80 m).

Therefore, the hillslopes at Horvat Haluqim are comparable with the upper part of the instrumented slope section at the Haluqim Anticline (Yair and Kossovsky, 2002; Yair and Raz-Yassif, 2004). Hydrological measurements of the Upper Channel at the latter slope section seem to involve runoff from both the Nezer Formation and the Shivta Formation. The geo-technical runoff coefficients of these formations are 79% and 70%, respectively (Wieler et al., 2016:155). Unfortunately, no

Table 3
The geological substratum of runoff catchment areas of ancient runoff farms, a cistern, and the Haluqim instrumented slope section, mentioned in the text, in relation to the geo-technical runoff coefficient of bedrock blocks measured by Wieler et al. (2016).

Geological Period	Geological Formation	Lithology	Geotechnical Runoff Coefficient (%)	Ancient Runoff Farms, a Cistern, and the Haluqim slope section		
Eocene	Matred	Limestone	87	Avdat Farm		
Eocene	Horsha	Chalk	48			
Santonian	Menuha	Chalk	45	Shivta Cistern		
Turonian	Nezer	Limestone	79	Shivta Farm	Horvat Haluqim terraced wadi	Slope section Haluqim Anticline
Turonian	Shivta	Limestone	70			
Turonian	Drorim	Soft Limestone	80			

Fig. 9. The hilly catchment of the 1st order eastern Terraced Wadi at Horvat Haluqim looking northward. Bedded limestone layers of the Turonian Nezer Formation are visible alternating with overlying strips of crusted loess soil mixed with stones. Notice the green coverage of annual wild cereals and herbaceous vegetation in the terraced wadi, after the winter rains (Photo H.J. Bruins 26-03-2007). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

hydrological results were published specifically of the Nezer Formation only. A moderate rainfall event of about 13 mm (Yair and Raz-Yassif, 2004:161) gave a runoff coefficient of 28% for the Upper Channel (Nezer and Shivta Formations). The very large rainfall events of 45.6 mm and 53.2 mm (Yair and Kossovsky, 2002) produced runoff coefficients in the Upper Channel of 65% and 52.7%, respectively.

Since most rainfall events in the central Negev Highlands are in the range of 3–10 mm (Sharon, 1972; Evenari et al., 1982), i.e. below the above 13 mm, the average annual runoff coefficient in our case for Horvat Haluqim should be lower than the above 28%, because the runoff coefficient relates also to rainfall amount.

Comparing also the size of the respective catchment areas, which is another very important factor in relation to average annual runoff coefficients (Shanan and Schick, 1980; Evenari et al., 1982; Shanan, 2000), the Upper Channel at the Haluqim Anticline comprises a watershed of 0.8 ha (Yair and Kossovsky, 2002). Our model accurately calculated the catchment area of each individual terraced wadi field at Horvat Haluqim, ranging from 0.10 ha to 0.36 ha (Table 4). Hence the respective watersheds of each terraced field are considerably smaller than the catchment size of the Upper Channel at the Haluqim Anticline. Therefore, in terms of watershed size, the runoff coefficients at Horvat Haluqim ought to be *larger* than at the Haluqim Anticline. On the other hand, the absence of the massive Shivta Formation along the hillslopes of Horvat Haluqim's eastern terraced wadi, may somewhat diminish the runoff coefficient, as compared to the Upper Channel measurements of the Haluqim Anticline.

Fig. 10. The eastern Terraced Wadi at Horvat Haluqim looking southward downstream, showing remains of ancient stone terrace walls. There is no colluvium at the lower slope, where bedded outcrops of hard limestone of the Turonian Nezer Formation, alternating with strips of crusted loess soil and stones, occur until the wadi bed. The hilly Eocene Avdat plateau is visible on the horizon in the south (Photo H.J. Bruins 06-03-2010).

Table 4
The results of our GIS-based hydrological model, showing the calculated size of individual agricultural fields and their related catchment areas. Runoff amounts are calculated by the model for a drought year, an average rainfall year, and for a very wet year, using in all these cases an average annual runoff coefficient of 10%. Both runoff and direct rainfall are combined in the subsequent columns, in order to show the total water amount received by each terraced field.

Field No.	Field Area (m^2)	Catchment Area (m^2)	Drought Year 34 mm Runoff (mm)	Drought Year 34 mm Runoff & Rainfall (mm)	Average Year 88 mm Runoff (mm)	Average Year 88 mm Runoff & Rainfall (mm)	Very Wet Year 188 mm Runoff (mm)	Very Wet Year 188 mm Runoff & Rainfall (mm)
1	179	2924	91	125	232	320	496	684
2	117	2507	108	142	277	365	593	781
3	255	3594	83	117	212	300	454	642
4	157	2159	82	116	210	297	447	635
5	125	991	62	96	158	246	338	526
6	107	1546	83	117	212	300	452	640
7	224	1203	52	86	133	221	283	471
8	183	1740	67	101	172	260	367	555
9	231	943	49	83	124	212	265	453
10	211	2551	76	110	195	283	416	604
11	334	1159	46	80	119	207	253	441
12	296	2751	66	100	170	258	363	551
13	156	1281	63	97	160	248	343	531

Concerning bedrock exposure of the Nezer Formation at the Horvat Haluqim eastern watershed, measured along transects from the water divide on the western hill spur to the water divide on the eastern hill spur (Fig. 9), bedrock surface coverage was found to be in the range of 17–57% (Bruins and Ore, 2008). Using Erdas Imagine based supervised land cover classification, we determined for the Horvat Haluqim watersheds that on average 23% of the surface is composed of bedrock outcrops, 71% is loess soil (often mixed with stones) overlying the bedrock in alternating strips, while vegetation cover is 6%.

Concerning the watershed of the Avdat Farm, we applied the same methodology of supervised land cover classification using Erdas Imagine. Our results show that bedrock surface coverage at the Avdat Farm watershed is only 3%, loess soil coverage (partly mixed with stones) is 93%, and vegetation cover is 4%. These figures underline the important contribution of loess covered areas in runoff production, as shown by the extensive and long-term hydrological measurements by Shanan. The crust on the loess makes it, under wet conditions, after absorbing 2–3 mm of rainfall, rather impermeable, thus producing significant amounts of runoff (Shanan and Schick, 1980; Evenari et al., 1982; Shanan, 2000).

The hillslope length at Horvat Haluqim ranges from ~40 to 80 m, which is much shorter than hillslopes at the southern watershed of the Avdat Farm. Concerning watershed size, the various conduit channels at the Avdat Farm drain watersheds ranging in size from 1.0 to 7.0 ha, being about 10–20 times larger than the watersheds (0.10–0.36 ha) of the individual terraced fields at Horvat Haluqim (Table 4). The average annual runoff coefficients of the above hillslope conduit catchments at the Avdat Farm range between 5% and 12.2% (Table 2). The very small runoff plots of 80 m^2 at the Avdat Farm, having a slope length of 20 m, have an average annual runoff coefficient of 25.4%.

Considering all the hydrological measurements and data at the Avdat Farm and at the instrumented slope section of the Haluqim Anticline, an average annual runoff coefficient of 10% for the hillslope catchments of the individual terraced fields at Horvat Haluqim seems a reasonable approximation, perhaps even too conservative.

The resulting runoff calculations of our model (Table 4) are based on precise determination of the catchment size of each individual terraced field, on the annual precipitation for each of three different rainfall years (an average rainfall year, 1989–90; a very wet year, 1991–92; a severe drought year, 1999–2000), and the approximated average annual runoff coefficient of 10%. Rainfall data are from the nearby meteorological station of the Israel Meteorological Service at Kibbutz Sede Boker (Fig. 2), at a distance of just about 1700 m from Horvat Haluqim.

4.2. Model calculated runoff yields during an average rainfall year, 1989-90

Rainfall during the year 1989–90 totalled 88 mm, which can be regarded as an average rainfall year, slightly below the long-term average of 98 mm at Kibbutz Sede Boker during the period 1970–2002 (Kafle and Bruins, 2009). Using a conservative average annual runoff coefficient of 10%, our model calculated runoff amounts received by the individual terraced fields, range from 119 to 232 mm (Table 4). Hence there are considerable differences between the respective 13 terraced fields in terms of runoff yields, as indicated by the model.

The direct rainfall of 88 mm is added to the runoff yields in the subsequent column (Table 4), to illustrate the total water amount received by each terraced field. Water quantities in the range of 200–300 mm were received by 9 of the 13 terraced fields in the eastern wadi (Fig. 11). The two fields, situated most upstream, obtained more water, in the range of 300–400 mm during an average rainfall year (Fig. 11).

Considering the potential performance of annual field crops with the combined water amounts of both rainfall and runoff, ranging from 207 to 365 mm during the rainy season, both barley and wheat may be grown successfully. Concerning perennial fruit trees, grapevines may suffice with about 350 mm of rainfall, which may be successful in some of the terraced fields. Perhaps the average annual runoff coefficient of 10%, used for the model calculations, has been too conservative, because trees are grown successfully by the Jewish National Fund in modern terraced wadi fields near Horvat Haluqim, as presented below in section 5.

4.3. Model calculated runoff yields during a very wet rainfall year 1991–92

The amount of rainfall during 1991–92 was 188 mm at the Sede Boker Meteorological Station near Horvat Haluqim. This was the wettest year ever recorded in Israel since the beginning of precipitation measurements. Calculated runoff amounts received by each individual terraced field with our model range from 253 to 593 mm (Table 4). Adding the direct rainfall of 188 mm to these amounts in the next column (Table 4) gives the total water amounts for each field. The variations for each terraced field are shown in Fig. 12.

Although the year 1991–92 was exceptional, years with comparatively large rainfall amounts are not rare. There were 15 years with rainfall amounts > 100 mm during the 32 year period 1970–2002 at the Sede Boker Meteorological Station. It is clear that many types of agricultural crops may be grown during such wet years, due to the

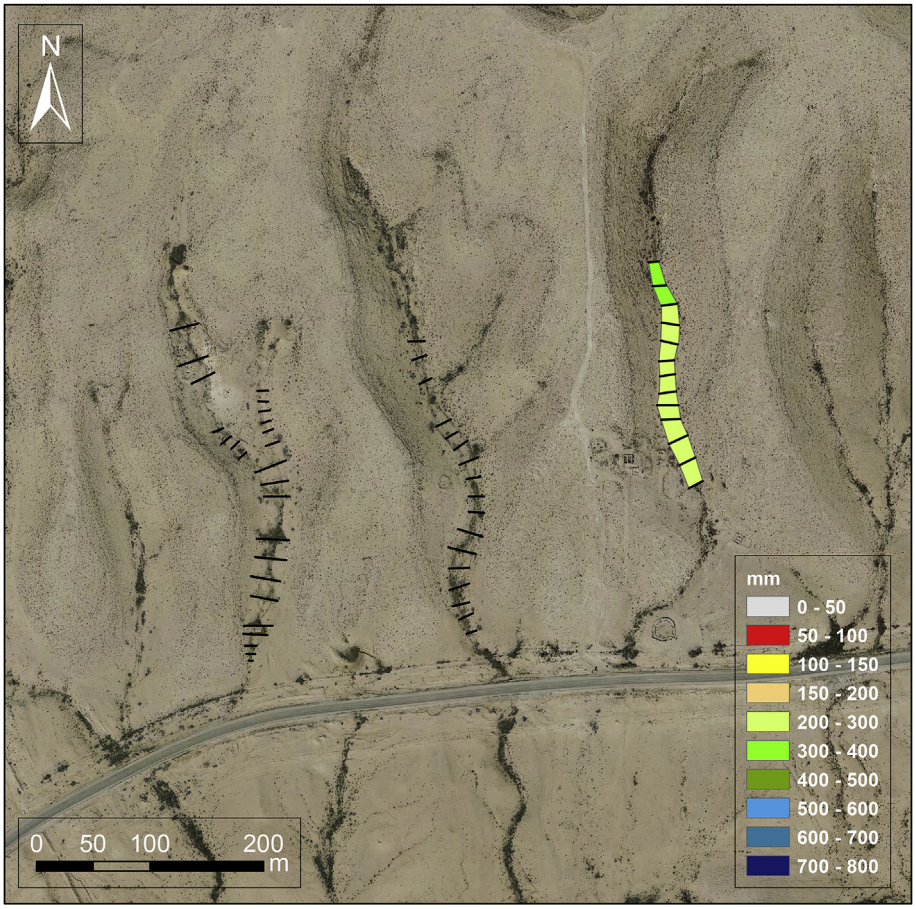

Fig. 11. Average rainfall year 1989–90. Combined rainfall and model calculated runoff water amounts received by each of the 13 terraced fields in the eastern wadi of Horvat Haluqim.

addition of runoff water. However, the potential bottleneck for perennial crops and trees are of course the drought years (Bruins and Lithwick, 1998), addressed in the next section.

4.4. Model calculated runoff yields during a severe drought year 1999–2000

The amount of annual rainfall in the area was only 34 mm during this harsh drought year. Calculated runoff amounts received by the individual terraced fields range from 46 to 108 mm (Table 4). Adding in the next column the direct rainfall amount shows that water amounts in the terraced fields range from 80 to 142 mm, as indicated by our model.

Therefore, in terms of agriculture, perhaps only barley may give a slight yield in some of the better watered terraced fields (Fig. 13). Otherwise, a drought year will lead to crop failure. The question is whether perennial trees can survive such severe drought years? The next section unmistakably proves that trees do survive drought years in nearby modern terraced wadi fields, similar to those at Horvat Haluqim, as well as at the reconstructed Shivta Farm.

5. Trees in the otherwise tree-less desert

Wadis of 1st stream order on the Haluqim Anticline were terraced by the Jewish National Fund some 1–2 km north-west of Horvat Haluqim along Road 40, around the year 2000 or slightly afterwards. These wadis had not been terraced in the past. Hence, there was no legal problem (Antiquities Law) to build modern terrace walls (Figs. 3 and 14) to facilitate tree growth.

The natural landscape surface is characterised, like at Horvat Haluqim, by bedded limestone of the Nezer Formation, partly covered by crusted loess soil and stones. The modern stone terrace walls captured runoff water (Figs. 3 and 14) from these geomorphic surfaces during rainfall events and trees were established successfully in the following years (Fig. 15). It is clear that in the period of about 14 years of tree growth, captured by Figs. 14 and 15, also drought years occurred. Statistically a drought year in Israel can be expected on average once every three years (Bruins, 2000).

Therefore, the trees may receive appreciable runoff water amounts even during drought years. Their survival may also relate to runoff water from previous wetter years. Such water may be held by capillary force for considerable time in the deeper loessial subsoil. Moreover, the reduction of water loss by evaporation was found to be related to the sealing properties of the crust that covers loess soils in the Negev (Sela et al., 2012). A model for seal hydraulic properties studied spatial variations of water content over an entire loess hillslope in the northern Negev (near Lehavim) in relation to the sealing effect of the surface crust (Sela et al., 2012).

The ancient Shivta Farm (Fig. 8), reconstructed by Evenari, Shanan and Tadmor in 1958, still shows many surviving fruit trees, including olive, pomegranate, fig, grapevine and carob. Obviously, these fruit trees have managed to survive many drought years, including one of the worst periods, 1998–2000, when a severe drought lasted for two consecutive years. Both the joint effect of soil texture of loess soils (usually silt-loam), having excellent water-holding properties, and the surface crust that reduces evaporation from the soil, serve to mitigate the effect of drought years.

Concerning the Avdat Farm, reconstructed by Evenari, Shanan and Tadmor in 1960, agriculture started in the 1960–61 rainfall year.

Fig. 12. Very wet rainfall year 1991–92. Combined rainfall and model calculated runoff water amounts received by each of the 13 terraced fields in the eastern wadi of Horvat Haluqim.

However, the next two years, 1961–62 and 1962–63, turned out to be drought years. The above investigators remarked: "*Nevertheless, even during these critical drought years the watersheds supplied sufficient water for the crops. It is true that growth and yield were marginal, but everything survived and some crops even thrived well*" (Evenari et al., 1982:191).

6. Final discussion and conclusions

Our approach, using a GIS-based hydrological model, opens an entirely new avenue to study ancient agricultural systems in the central Negev desert, because each and every terraced field can be investigated in a non-invasive manner. The availability of high resolution LiDAR data and detailed orthophoto images enables the generation of detailed DEMs and classification of land covers. These components constitute the infrastructure for accurate spatial calculations of boundaries and size assessments of each catchment area that contributes runoff to a specific ancient agricultural terraced field and cistern. The model is also suited for modern applications to develop rainwater harvesting projects.

However, more research is required to establish applicable rules to estimate more precisely the runoff coefficients that ought to be used in case-sensitive model calculations. More research is also required to test the model against hydrological data measured with conventional hydrographs and other instrumented hydrological equipment.

Following the detailed investigations by Yair and his colleagues of an instrumented hillslope at the Haluqim Anticline, there has been a tendency in some of the literature to overemphasize the significance of bedrock surfaces in runoff production. The systematic and extensive hydrological results of the Avdat Farm (Shanan and Schick, 1980; Evenari et al., 1982; Shanan, 2000) should not be ignored. These results clearly show that also crusted loess soil surfaces, which clearly dominate in areal extent over clean bedrock surfaces in the Negev Highlands, can produce significant amounts of runoff.

The apparent lack of terraced wadi fields with stone terrace walls in the loess region north of the central Negev Highlands, as noted by Yair (1983), seems not to be related to a lack of runoff potential but is probably caused by other factors. First, the lack of hard bedrock outcrops in the northern Negev makes it very costly to quarry and move from afar limestone building stones to make stone terrace walls in the wadi beds. Mudbricks were often used to build houses in areas with loess or alluvial sediments. However, mudbricks are not suitable to build terrace walls in wadi beds to withstand runoff and floodwater flows. Eocene chalk does occur below the extensive loess cover in this region, but even chalk is not used for making stone terrace walls. Second, the geomorphology in this region of the northern Negev shows many examples of V-shaped valleys which are too narrow in the wadi bed to facilitate enough space for agricultural fields.

Nevertheless, some ancient agricultural fields and ancient farm buildings were discovered during archaeological surveys (Map 132) in the Nahal Beqa area (Baumgarten, personal communication, 2011; Bruins, 2012:32). Bedouin living in the area today use bulldozers to make terrace walls of soil in suitable valleys to capture runoff from loess-covered catchments to sustain fruit trees, particularly olives.

Whether used in typical loess areas or in areas with both bedrock exposures and loess-covered surfaces, the critical issue for success of the GIS-based hydrological model is the correct approximation of the runoff coefficient in each particular case.

Our calculations of runoff yields during an average rainfall year, a

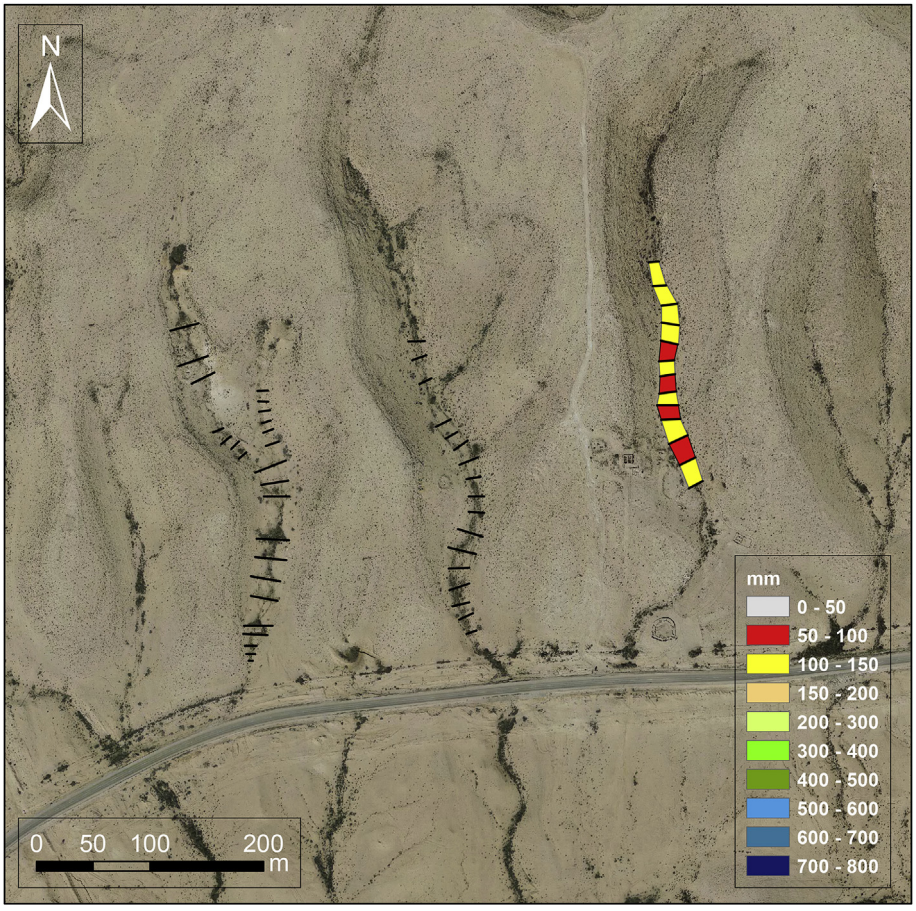

Fig. 13. Severe drought year 1999–2000. Combined rainfall and model calculated runoff water amounts received by each of the 13 terraced fields in the eastern wadi of Horvat Haluqim.

Fig. 14. A modern stone terrace wall, built by the Jewish National Fund in a 1st order wadi in the Haluqim hills to enable the planting and growth of trees in the desert. The captured runoff water was generated during a rainfall event on the adjacent hillslopes composed of hard limestone of the Turonian Nezer Formation, covered extensively by crusted loess soil and stones. This area is about 1.5 km north-west of the archaeological site of Horvat Haluqim (Photo by H.J. Bruins, 14-01-2004).

Fig. 15. The same area as in Fig. 14, but 14 years later, showing successful tree growth in the desert, based on the capture of runoff water. Notice again that the surface of the surrounding slopes is extensively covered by crusted loess soils and rock fragments, overlying hard limestone layers of the Turonian Nezer Formation (Photo by H.J. Bruins, 06-08-2018).

very wet year and a severe drought year also imply that the model can be applied to simulate and study past climatic variations, as well as future climatic change. Thus our model has the potential to study possible impacts on agriculture based on runoff/floodwater capture in the Negev, as well as in other desert and dryland regions in the world.

Acknowledgements

We are grateful to the Social Sciences and Humanities Faculty of Ben-Gurion University of the Negev and the Israel Ministry of Science, Technology and Space for funding of the MA research of the second author, Hodaya Bithan-Guedj. We express our gratitude to the Stichting Midbar Foundation for funding the procurement of the aerial LiDAR and orthophotography of Horvat Haluqim. We thank the Israel Antiquities Authority for the various research permissions received by the first author (Bruins) for investigations at Horvat Haluqim.

References

Ackermann, O., Svoray, T., Haiman, M., 2008. Nari (calcrete) outcrop contribution to ancient agricultural terraces in the Southern Shephelah, Israel: insights from digital terrain analysis and a geoarchaeological field survey. J. Archaeol. Sci. 35, 930–941.

Arkin, Y., Braun, M., 1965. Type Sections of Upper Cretaceous Formations in the Northern Negev (Southern Israel). Geological Survey of Israel, Stratigraphic Sections 2a, Jerusalem.

Ashkenazi, E., Avni, Y., Avni, G., 2012. A comprehensive characterization of ancient desert agricultural systems in the Negev Highlands of Israel. J. Arid Environ. 86, 55–64.

Avni, G., Porat, N., Avni, Y., 2013. Byzantine–early Islamic agricultural systems in the Negev highlands: stages of development as interpreted through OSL dating. J. Field Archaeol. 38 (4), 332–346.

Avni, Y., Porat, N., Avni, G., 2012. Pre-farming environment and OSL chronology in the Negev highlands, Israel. J. Arid Environ. 86, 12–27.

Bar-Matthews, M., Ayalon, A., 2011. Mid-Holocene climate variations revealed by high-resolution speleothem records from Soreq Cave, Israel and their correlation with cultural changes. Holocene 21 (1), 163–171.

Bartov, Y., 2004. Sedimentary fill analysis of a continental basin – The Late Pleistocene Dead Sea. Unpublished PhD dissertation. The Hebrew University of Jerusalem.

Bookman (Ken-Tor), R., Enzel, Y., Agnon, A., Stein, M., 2004. Late Holocene lake levels of the Dead Sea. Geol. Soc. Am. Bull. 116, 555–571. https://doi.org/10.1130/B25286.1.

Bruins, H.J., 1986. Desert Environment and Agriculture in the Central Negev and Kadesh-Barnea during Historical Times. Published Ph.D. Dissertation. Wageningen University, Stichting Midbar Foundation, Nijkerk.

Bruins, H.J., 1990. Ancient agricultural terraces at nahal Mitnan. Atiqot 10, 127–128 (Hebrew), 22*–28* (English).

Bruins, H.J., 1994. Comparative chronology of climatic and human history in the southern Levant from the late Chalcolithic to the Early Arab Period. In: Bar-Yosef, O., Kra, R. (Eds.), Late Quaternary Chronology and Paleoclimates of the Eastern Mediterranean. Radiocarbon, Tucson, pp. 301–314.

Bruins, H.J., 2000. Drought hazards in Israel and Jordan: policy recommendations for disaster mitigation. In: Wilhite, D.A. (Ed.), Drought: A Global Assessment. Volume II. Routledge, London, pp. 178–193.

Bruins, H.J., 2012. Ancient desert agriculture in the Negev and climate-zone boundary changes during average, wet and drought years. J. Arid Environ. 86, 28–42.

Bruins, H.J., Evenari, M., Nessler, U., 1986. Rainwater harvesting agriculture for food production in arid zones: the challenge of the African famine. Appl. Geogr. 6, 13–32.

Bruins, H.J., Jongmans, A., 2012. Micromorphology of ancient agricultural terraces in the Negev desert, Horvat Haluqim (Israel). In: Poch, R.M., Casamitjana, M., Francis, M.L. (Eds.), Proceedings of the 14th International Working Meeting on Soil Micromorphology. International Union of Soil Sciences & University of Lleida, Lleida, pp. 292–295.

Bruins, H.J., Lithwick, H., 1998. Proactive planning and interactive management in arid frontier development. In: Bruins, H.J., Lithwick, H. (Eds.), The Arid Frontier: Interactive Management of Environment and Development. Kluwer/Springer, Dordrecht, Boston, London, pp. 3–29.

Bruins, H.J., Ore, G., 2008. Runoff from loess or bedrock? Hillslope geoarchaeology of ancient runoff farming systems at Horvat Haluqim and Har Eldad in the central Negev desert. Isr. J. Earth Sci. 57 (3–4), 231–247.

Bruins, H.J., Van der Plicht, J., Haiman, M., 2012. Desert habitation history by ^{14}C dating of soil layers in rural building structures (Negev, Israel): preliminary results from Horvat Haluqim. Radiocarbon 54 (3–4), 391–406.

Bruins, H.J., Van der Plicht, J., 2017a. Iron Age agriculture – a critical rejoinder to "settlement oscillations in the Negev Highlands revisited: the impact of micro-archaeological methods. Radiocarbon 59 (1), 1–16.

Bruins, H.J., Van der Plicht, J., 2017b. Dating of Iron Age agriculture in the Negev highlands: a response to shahack-gross and finkelstein. Radiocarbon 59 (4), 1233–1239.

Bruins, H.J., Segal, I., Van der Plicht, J., 2018. Bronze chisel at Horvat Haluqim (central Negev highlands) in a sequence of radiocarbon dated late Bronze to Iron Age I layers. In: Ben-Yosef, E. (Ed.), Mining for Ancient Copper: Essays in Memory of Beno Rothenberg. Monograph Series 37, Sonia and Marco Nadler Institute of Archaeology. Tel Aviv University, Tel Aviv & Eisenbrauns, Winona Lake, IN, pp. 297–308.

Cohen, R., 1976. Excavations at Horvat Haluqim. Atiqot 11, 34–50.

Emmett, W.W., 1970. The Hydraulics of Overland Flow on Hillslopes. Geological Survey Professional Paper 662-A, United States Government Printing Office, Washington.

Erez Edelson, R., 2004. Sedentary Zone in the Negev during the Byzantine Period: Settlement Distribution and Runoff Farming. Unpublished Ph.D. dissertation, Bar-Ilan University, Ramat Gan.

Evenari, M., Shanan, L., Tadmor, N., Aharoni, Y., 1958. The ancient desert agriculture of the Negev, III. Early beginnings. Isr. Explor. J. 8, 231–268.

Evenari, M., Shanan, L., Tadmor, N.H., 1982. The Negev: the Challenge of a Desert, 2nd revised edition. Harvard University Press, Cambridge MA.

Fujii, S., 2007. Wadi Abu Tulayha and Wadi Ruweishid ash-Sharqi: an investigation of PPNB Barrage Systems in the Jafr Basin. Neo-Lithics 2 (07), 6–17.

Fuks, D., Ackermann, O., Ayalon, A., Bar-Matthews, M., Bar-Oz, G., Levi, Y., Maeir, A.M., Weiss, E., Zilberman, T., Safrai, Z., 2017. Dust clouds, climate change and coins:

consiliences of palaeoclimate and economy in the Late Antique southern Levant. Levant 49 (2), 205–223.
Goldreich, Y., 2003. The Climate of Israel. Springer, New York.
Greenbaum, N., Schick, A.P., Baker, V.R., 2000. The palaeoflood record of a hyperarid catchment, Nahal Zin, Negev desert, Israel. Earth Surf. Process. Landforms 25, 951–971.
Kafle, H., Bruins, H.J., 2009. Climatic trends in Israel 1970–2002: warmer and increasing aridity inland. Clim. Change 96, 63–77.
Kagan, E.J., Langgut, D., Boaretto, E., Neumann, F.H., Stein, M., 2015. Dead Sea levels during the Bronze and Iron ages. Radiocarbon 57 (2), 237–252 2015.
Kedar, Y., 1967. The Ancient Agriculture in the Negev Mountains. Bialik Institute, Jerusalem (in Hebrew).
Lavee, H., Yair, A., 1990. Spatial variability of overland flow in a small arid basin. Int. Assoc. Hydrol. Sci. (IAHS) 189, 105–120.
Lavee, H., Poesen, J., Yair, A., 1997. Evidence of high efficiency of water harvesting by ancient farmers in the Negev desert, Israel. J. Arid Environ. 35, 341–348.
Litt, T., Ohlwein, C., Neumann, F.H., Hense, A., Stein, M., 2012. Holocene climate variability in the Levant from the Dead Sea pollen record. Quat. Sci. Rev. 49, 95–105.
Offer, Z.Y., Goossens, D., 2001. Ten years of aeolian dust dynamics in a desert region (Negev desert, Israel): analysis of airborne dust concentration, dust accumulation and the high-magnitude dust events. J. Arid Environ. 47, 211–249.
Ore, G., Bruins, H.J., 2012. Design features of ancient agricultural terrace walls in the Negev desert: human-made geodiversity. Land Degrad. Dev. 23, 409–418.
Rubin, R., 1991. Settlement and agriculture on an ancient desert frontier. Geogr. Rev. 81 (2), 197–205.
Sela, S., Svoray, T., Assouline, S., 2012. Soil water content variability at the hillslope scale: impact of surface sealing. Water Resour. Res. 48, W03522. https://doi.org/10.1029/2011WR011297.
Shanan, L., 1975. Rainfall and Runoff Relationships in Small Watersheds in the Avdat Region of the Negev Desert Highlands. Unpublished Ph.D. dissertation, The Hebrew University of Jerusalem.
Shanan, L., 2000. Runoff, erosion, and the sustainability of ancient irrigation systems in the central Negev desert. Int. Assoc. Hydrol. Sci. (IAHS) 261, 75–106.
Shanan, L., Schick, A.P., 1980. A Hydrological Model for the Negev desert highlands: effects of infiltration, runoff and ancient agriculture. Hydrol. Sci. Bull. 25, 269–282.
Sharon, D., 1972. The spottiness of rainfall in desert areas. J. Hydrol. 17, 161–175.
Sneh, A., Avni, Y., Bartov, Y., Zilberman, E., Braun, M., Lasman, N., Weiberger, R., 2011. Geological Map of Shivta, Sheet 18-III, 1:50,000. Geological Survey of Israel, Jerusalem.
Svoray, T., 2004. Integrating automatically processed SPOT HRV Pan imagery in a DEM-based procedure for channel network extraction. Int. J. Remote Sens. 25, 3541–3547.
Tarboton, D.G., 1997. A new method for the determination of flow directions and upslope areas in grid digital elevation models. Water Resour. Res. 33 (2), 309–319.
UNEP, 1997. In: Middleton, N.J., Thomas, D.S.G. (Eds.), World Atlas of Desertification, second ed. Arnold, London.
Wieler, N., Avni, Y., Rosensaft, M., 2016. The significance of the geological strata on desert runoff agriculture: indications for stable desert environment over the last 1600 years in southern Israel. J. Arid Environ. 135, 147–163.
Yair, A., 1983. Hillslope hydrology, water harvesting and areal distribution of some ancient agricultural systems in the northern Negev desert. J. Arid Environ. 6, 283–301.
Yair, A., Sharon, D., Lavee, H., 1980. Trends in runoff and erosion processes over an arid limestone hillside, northern Negev, Israel. Hydrol. Sci. Bull. 25, 243–255.
Yair, A., Kossovsky, A., 2002. Climate and surface properties: hydrological response of small arid and semi-arid watersheds. Geomorphology 42 (1–2), 43–57.
Yair, A., Raz-Yassif, N., 2004. Hydrological processes in a small arid catchment: scale effects of rainfall and slope length. Geomorphology 61, 155–169.